Fermi National Accelerator Laboratory

TM-1583
[SSC-N-602]

Multilayer Insulation (MLI) in the Superconducting Super Collider - a Practical Engineering Approach to Physical Parameters Governing MLI Thermal Performance*

J. D. Gonczy, W. N. Boroski, and R. C. Niemann
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois

March 1989

* Presented by J. D. Gonczy at the 1989 International Industrial Symposium on the Super Collider (IISSC), New Orleans, Louisiana, February 8-10, 1989.

Operated by Universities Research Association, Inc., under contract with the United States Department of Energy

MULTILAYER INSULATION (MLI) IN THE SUPERCONDUCTING SUPER COLLIDER - A PRACTICAL ENGINEERING APPROACH TO PHYSICAL PARAMETERS GOVERNING MLI THERMAL PERFORMANCE

J.D. Gonczy, W.N. Boroski, and R.C. Niemann

Fermi National Accelerator Laboratory
P.O. Box 500
Batavia, Illinois 60510

ABSTRACT

Multilayer insulation (MLI) is employed in cryogenic devices to control the heat load of those devices. The physics defining the thermal performance of an MLI system is extremely complex due to the thermal dynamics of numerous interdependent parameters which in themselves contribute differently depending on whether boundary conditions are transient or steady-state. The Multilayer Insulation system for the Superconducting Super Collider (SSC) consists of full cryostat length assemblies of aluminized polyester film, fabricated in the form of blankets, and installed as blankets to the 4.5K cold mass, and the 20K and 80K thermal radiation shields. Approximately 40,000 blankets will be required in the 10,000 cryogenic devices comprising the SSC accelerator. Each blanket will be nearly 56 feet long by 6 feet wide and will consist of as many as 32 reflective and 31 spacer layers of material. Discussed are MLI material choices, and the physical parameters which contribute to the operational performance of MLI systems. Disclosed is a method for fabricating MLI blankets by employing a large diameter winding mandrel having a circumference sufficient for the required blanket length. The blanket fabrication method assures consistency in mass produced MLI blankets by providing positive control of the dimensional parameters which contribute to the MLI blanket thermal performance. The fabrication method can be used to mass produce prefabricated MLI blankets that by virtue of the product have inherent features of dimensional stability, three-dimensional uniformity, controlled layer density, layer-to-layer registration, interlayer cleanliness, and interlayer material to accommodate thermal contraction differences.

INTRODUCTION

The objective of the SSC MLI system is to limit cryostat heat leak from thermal radiation and residual gas conduction to the low levels specified by the SSC magnet systems design criteria.[1] The MLI system must maintain these low heat leak levels during the 20 plus years lifetime of the SSC while in an environment of nuclear irradiation and for extended periods of operational upset conditions including thermal cycles and poor insulating vacuum.

Crucial to the development of an MLI system for the SSC is a solid understanding of the characteristics which contribute to the overall performance of the MLI system. One must assess each parameter's influence on the performance level of the MLI, and under what operating conditions, if any, are the dominate parameters made less prevalent. Laboratory measurements continue to work toward resolving these questions by attempting to quantify the components of heat transfer in MLI. However, a definitive MLI system has yet to be designed, and there continues to be philosophical differences between partisans of specific MLI systems; each advocate having his particular system certified with laboratory results. While each physically different MLI system offers specialized performance characteristics, many other desirable traits are sacrificed. The final MLI solution may be found in a hybrid compromise of many MLI systems.

Equal in importance with laboratory measurements are concerns regarding the installation of the MLI system in the SSC cryostat. These concerns are generally recognized during cryostat operation as differences between the calculated heat leak to the cryostat, based on laboratory measurements, and the actual heat leak measured in the field. At the root of these differences is the relative inability to duplicate, in a practical manner at installation, the same MLI geometry and boundary conditions as was tested in the laboratory.

Historically, heat leak differences that varied by factors of 2 or 3 were regarded as MLI systems having good results. However, this celebrated view of heat leak in an aggregate of 10,000 SSC cryostats is not affordable, since the ultimate operating cost of the SSC depends principally on the ability to prevent heat leak to the cryogens. An essential requirement of the SSC MLI system is that the MLI geometry measured in the laboratory is, in fact, duplicated 40,000 times in the 10,000 SSC cryogenic devices.

Apart from the laboratory measurements, the challenges to developing a practical MLI system for the SSC which is both predictable and consistent in thermal performance are: 1) to design an MLI system that lends itself to mass fabrication and mass installation techniques, and which automates decision making during installation of the MLI blanket in the SSC cryostat; 2) to develop a fabrication method that uses ordinary production skills; and 3) to develop an apparatus to achieve the blanket design in a cost effective manner. These challenges have been accomplished and are described below.

SSC MAGNET CRYOSTAT OVERVIEW

Major Cryostat Components - The major components of the SSC cryostats are the cryogenic piping, the cold mass assembly which includes the superconducting magnets, the thermal radiation shields, the support system for suspending the cold mass assembly and thermal shields, the multi-layer insulation system, the vacuum vessel, and the interconnections between cryostats.[2] See Fig. 1.

In each SSC cryostat, the cold mass assembly housing the superconducting magnets is surrounded by several regions of progressively higher temperature. The region directly surrounding the cold mass assembly is the 4.5K region which is cooled by cryogenic piping containing liquid helium at 4.3K. An MLI blanket containing five reflective layers is spiral wrapped around the main body sections of the cold mass to a thickness of ten layers.

A second region known as the 20K region surrounds the 4.5K region. The 20K region is cooled by cryogenic piping containing gaseous helium at 20K. The 20K region is bounded by an aluminum thermal shield around which an MLI blanket assembly of thirty-two reflective layers is wrapped.

A third region known as the 80K region surrounds the 20K thermal shield. The 80K region is cooled by cryogenic piping containing liquid nitrogen at 77K. Bounding the 80K region is another thermal shield formed from aluminum sheet. Two separately installed MLI blanket assemblies each consisting of thirty-two reflective layers are wrapped around the 80K shield.

A vacuum containment vessel at room temperature (300K) surrounds the 80K shield.

PARAMETERS AFFECTING MLI HEAT TRANSFER

Radiation Heat Leak and Thermal Boundaries - Heat transfer by thermal radiation is from hot to cold, and varies directly as the fourth power temperature difference between the communicating surfaces. Thermal radiation also varies directly with a material property called surface emissivity. Shiny aluminized surfaces like those used in MLI reflect substantially more thermal radiation than they absorb; and for heat flowing through the MLI to become constant, the heat that is absorbed by each MLI layer must be radiated away or emitted. Since the reflective aluminized layer absorbs a relatively low level of thermal radiation, it consequently radiates thermal energy at a low level. The physical characteristics and surface condition of the material which combine to reflect thermal radiation, and therefore to emit heat at low levels, is described as a measure of the emissivity of the surface. As such, low emissivity surfaces are good inhibitors of thermal radiation. The surface emissivity of the MLI reflector is a quality-controlled property of the MLI and is described to the MLI vendor in a materials specification.

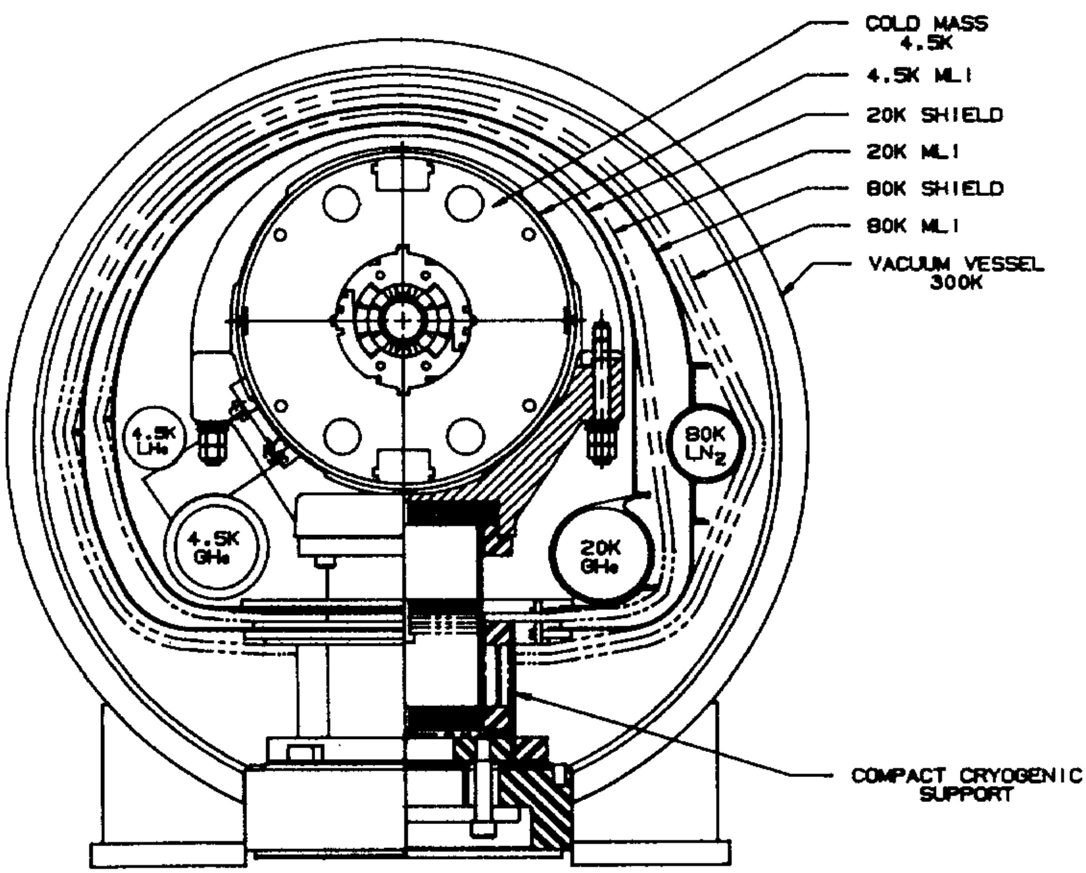


Fig. 1. SSC Cryostat Cross-section

A functional MLI system consists of many layers of low emissivity surfaces which reflect thermal energy by providing multiple adjacent layers of low emissivity surfaces which are relatively close in temperature. The layers also serve as a barrier to impede gas conduction. A low thermal conductive material is often used as a spacer to distance each reflective layer as the reflective layers are installed uniformly to encapsulate the cold surface. The heat flux through the MLI varies inversely with the number of reflective layers, and is a function of the layer density or number of reflective layers per unit thickness of MLI. MLI systems are more cost-effective when installed as multilayer blankets rather than as many individually installed layers.

Insulating Vacuum and Residual Gas Conduction - A portion of the heat that is transferred in a cryostat occurs by means of residual gas conduction. To limit the heat leak contribution by gas conduction to a negligible amount, the concentration of gas molecules is reduced by evacuation of the gases to an insulating vacuum level. At this insulating vacuum level, the residual gases because of their reduced number are more likely to collide with the surfaces of their confinement boundaries and not so much with each other. Heat transfer is conducted by individual gas molecules traveling between hot and cold confinements, and the amount of heat transferred by this molecular flow varies directly with the number of gas molecules present as measured by the residual gas pressure.

A paramount objective of the SSC design criteria is the ability to establish and maintain a stable insulating vacuum; and since the main impediment to a credible vacuum is the evacuation of interstitial blanket spaces, serious thought regarding evacuation was given to the blanket design. In spite of an apparent advantage to the evacuation process that a perforated MLI blanket might offer with its larger conductances for gas flow, it is noted that as the evacuated gases approach molecular flow, the perforations become ineffectual. It has been demonstrated that interstitial pressures in perforated MLI remain above 1×10^{-4} mmHg during room temperature evacuations.[3] The judgement at this time is for non-perforated reflective materials instead of the perforated for the SSC blanket design, although the design option to perforate part or all of future MLI systems for the SSC remains open. The considerations here are twofold. Firstly, the cost of perforating the MLI can be as much as one and a half times the cost of the aluminized material itself. And secondly, the SSC cryostats are certain to experience vacuum perturbations and perhaps situations with prolonged poor vacuum conditions due to leaks.

The initial disadvantage of a longer pump-down time for a non-perforated MLI has been discounted in favor of the long term advantages of the blanket in providing greater resistance to upset conditions. Granted, the initial pump-down time would be longer with the non-perforated blanket due to its poor evacuation conductances, but there is ample time to establish the pre-cooldown vacuum as the 53 miles of accelerator rings are put in place. By similar reasoning, the non-perforated blanket would show less sensitivity to transient vacuum conditions in that the diffusion of gases through a non-perforated blanket would take longer because of the poor conductance to gaseous flow in the reverse direction. An objective of the MLI blanket design is to foster a dampening effect to heat flow so that critical time required to recover from an upset condition is increased.

Table 1 lists for comparison some important material property considerations for MLI.

Table 1. Comparison of MLI Material Properties

	POLYESTER	POLYIMIDE	POLYAMIDE
TRADE NAME†	MYLAR, REEMAY, DACRON	KAPTON	NYLON, CEREX
MOISTURE ABSORPTION [7,8,9]	0.4% @ 50% Rh REEMAY SPUNBONDED 0.5% @ 98% Rh	1.3% @ 50% Rh ———	8.0% @ 50% Rh CEREX SPUNBONDED 3–5% @ 95% Rh
OUTGASSING [4]	DACRON NET 1.1×10^{-4} g/g DOUBLE ALUMINIZED MYLAR 2.6×10^{-3} g/g	——— DOUBLE ALUMINIZED KAPTON 3.1×10^{-3} g/g 3.9×10^{-3} g/g	NYLON NET 4.0×10^{-2} g/g ———
RADIATION DAMAGE [6,7]	5.7×10^{8} RAD (50% MAX. MECHANICAL)	5.0×10^{9} RAD (50% MAX. MECHANICAL)	7.0×10^{7} RAD (50% MAX. MECHANICAL)
IRRADIATION GAS [6,7]	3–5 ml/g @ 10^{9} RAD H_2(70%), CO_2(20%), CO(10%)	———	20–25 ml/g @ 10^{9} RAD H_2(52%), CO(20%), CO_2(12%), N_2(8%), O_2(3%)

† DUPONT DE NEMOURS & CO; REEMAY INC; JAMES RIVER CORP.

Outgassing and Irradiation Gas Evolution - In a vacuum, gases are boiled from material surfaces in what is called "normal outgassing" of those surfaces. Since all cryostat components including the MLI must be maintained in an insulating vacuum, cleanliness constraints must be asserted to keep the vacuum space substantially free of contaminants. Excessive boiling from high vapor pressure contaminants in the vacuum system will increase the time and energy necessary to establish the cryostat design vacuum. During evacuation at room temperature, the major gas constituent of normal outgassing is water vapor which comprises approximately 95% of the evolved gases.[4] Gas evolving from materials during nuclear irradiation (operation of the accelerator) is also a significant consideration which must be addressed when choosing materials to be used in the cryostat vacuum envelope.

MLI Material Choices - The plastic materials used in the SSC blanket design are comprised entirely of polyester plastics. See Table No. 2. The blanket incorporates 32-reflective layers of double aluminized polyethylene terepththalate (PET) film, each separated by a single thin spacer layer of spunbonded PET material. A thick layer of spunbonded PET material covers the blanket top and bottom, and positions polyester hook and loop fasteners at the blanket edges. The fasteners are secured to the cover layer by sewing. The multiple blanket layers and cover layers are sewn together as an assembly along both blanket edges. Polyester thread is used in all sewing processes.

Dimensional Parameters Considered by the Blanket Design - Each MLI blanket for the SSC will be fitted with openings through which the support system for the cold mass and shield assemblies will penetrate. These holes also serve as evacuation ports which access the interstitial spaces between the many blanket layers. Interlayer registration of the holes through the MLI blanket must be maintained during the logistics of fabrication, handling, and installation of the 56 feet long by 6 feet wide MLI blankets. Also critical to the thermal performance of the MLI system is a uniform MLI layer density. Uniform layer density using previous MLI fabrication techniques has been extremely difficult to maintain at installation. Proper alignment of the blanket layers in the length and width dimensions and control of MLI layer density is assured by means of sewing together the multiple layers of the blanket along each blanket edge for the entire length of the blanket.

Table 2. SSC MLI Blanket Materials

BLANKET COMPONENT	MATERIAL	DESCRIPTION	COMPANY
REFLECTOR	ALUMINUM via VACUUM DEPOSITION	ALUMINIZED METAL COATING; TWO SIDES 350 ANGSTROMS THICK, D.C. RESISTANCE OHMS/SQUARE = 0.9 OHMS TOLERANCE (+0.1)(-0.0) EMISSIVITY <0.03.	MULTIPLE VENDORS
REFLECTOR SUBSTRATE	POLYETHYLENE TEREPTHTHALATE	FLAT FILM, 1 MIL THICK, NO PERFORATIONS	DUPONT & CO.
SPACER	POLYETHYLENE TEREPTHTHALATE	SPUNBONDED POLYESTER, 4 MIL THICK, 0.5 OZ/YD^2	REEMAY, INC.
COVER LAYERS	POLYETHYLENE TEREPTHTHALATE	SPUNBONDED POLYESTER, 9 MIL THICK, 1.35 OZ/YD^2	REEMAY, INC.
HOOK FASTENER	POLYESTER	HOOK #80, WHITE #012 WIDTHS: 1 INCH & 2 INCH	VELCRO USA, INC.
LOOP FASTENER	POLYESTER	LOOP #2000, WHITE #012 WIDTH: 1 INCH	VELCRO USA, INC.
THREAD	POLYESTER	V125 WHITE	BELDING CORTICELLI THREAD CO.

During the operation of the SSC, the multilayer insulation blankets are subjected to extreme temperature gradients along their thicknesses causing the layers nearest the cryogenic structure to experience dimensional contraction to a greater extent than the layers furthest from the cryogenic structure. Prior fabrication techniques have failed to account for the dimensional response of the blanket over the entire temperature range of the insulated cryogenic structure. The SSC blanket fabrication method accommodates MLI material thermal contraction in its length and width dimensions to temperature decreases as low as 4.5 Kelvin.

MLI BLANKET FABRICATION

Pictured in Fig. 2 is a large diameter winding apparatus used to fabricate the MLI blankets for the 4.5K cold mass, and the 20K and 80K shields. The apparatus consists of a rotatable mandrel with a fixed diameter of approximately 18 feet and an outer surface that is crowned with a convex cross-section. Accessory supply spools hold the blanket reflective and spacer materials. The function of the apparatus is to spiral wrap the appropriate number of MLI blanket layers around the mandrel. Since each wrap of MLI material increases the circumference of the mandrel, each successive layer of material is slightly greater in length than the preceding layer. Likewise in the transverse direction across the crowned surface, each successive layer is wound on an increasing circumference. The finished blanket is then bound together at its edges by rotating the blanket through a stationary sewing machine. A single cut is made directly across the width of the MLI, and the blanket is removed from the mandrel. The resulting MLI blanket has sufficient length and width for an SSC blanket assembly. In addition, there is locked between the parallel sewn seams: dimensional stability, three-dimensional uniformity, controlled layer density, interlayer registration, interlayer cleanliness, and extra material in successive layers in the length and width directions to aid thermal contraction, since the last layer wrapped on the mandrel is designated for installation as the first layer installed against the cold surface to be insulated. Fig. 3 shows an 80K inner MLI blanket for the SSC Dipole Magnet Design B Cryostat.

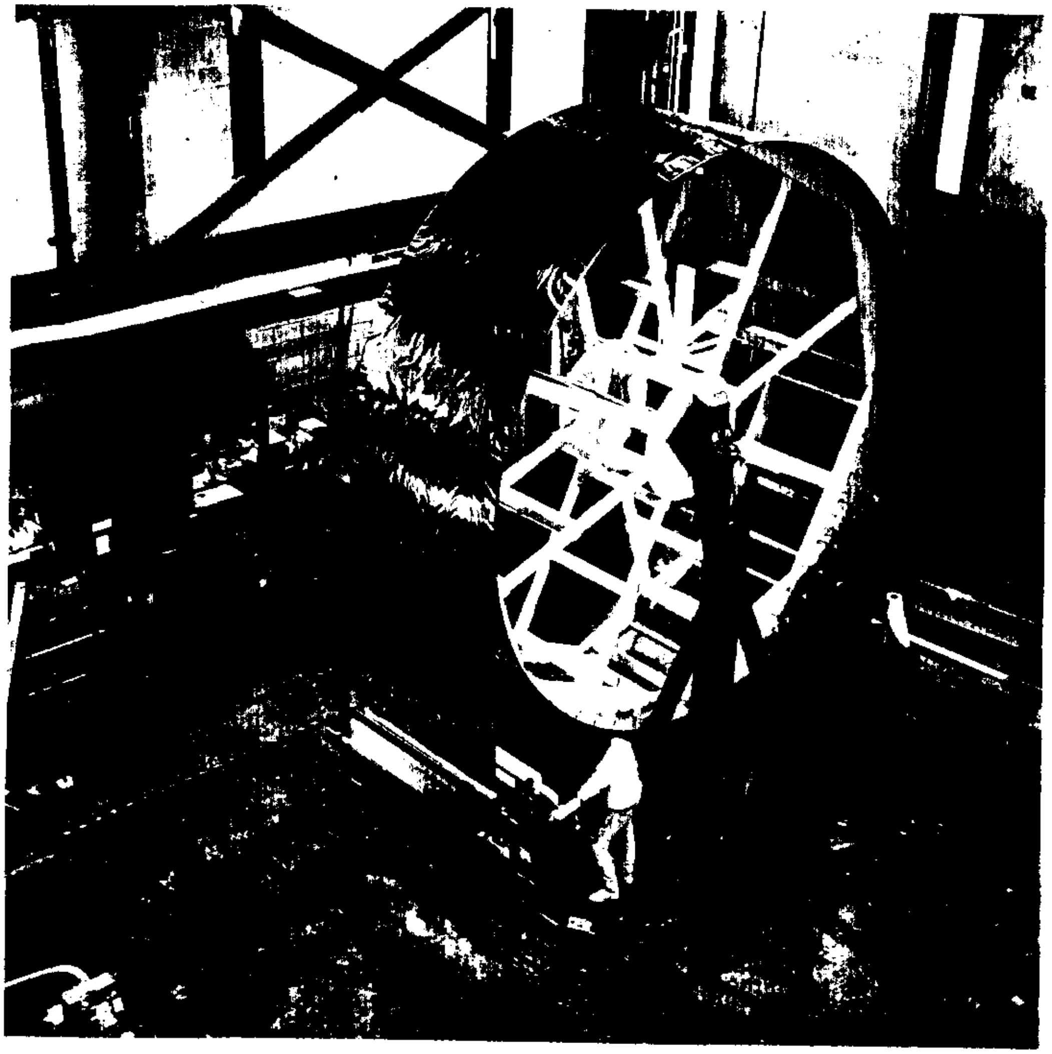


Fig. 2. Large Diameter Winding Apparatus for MLI Blanket Production

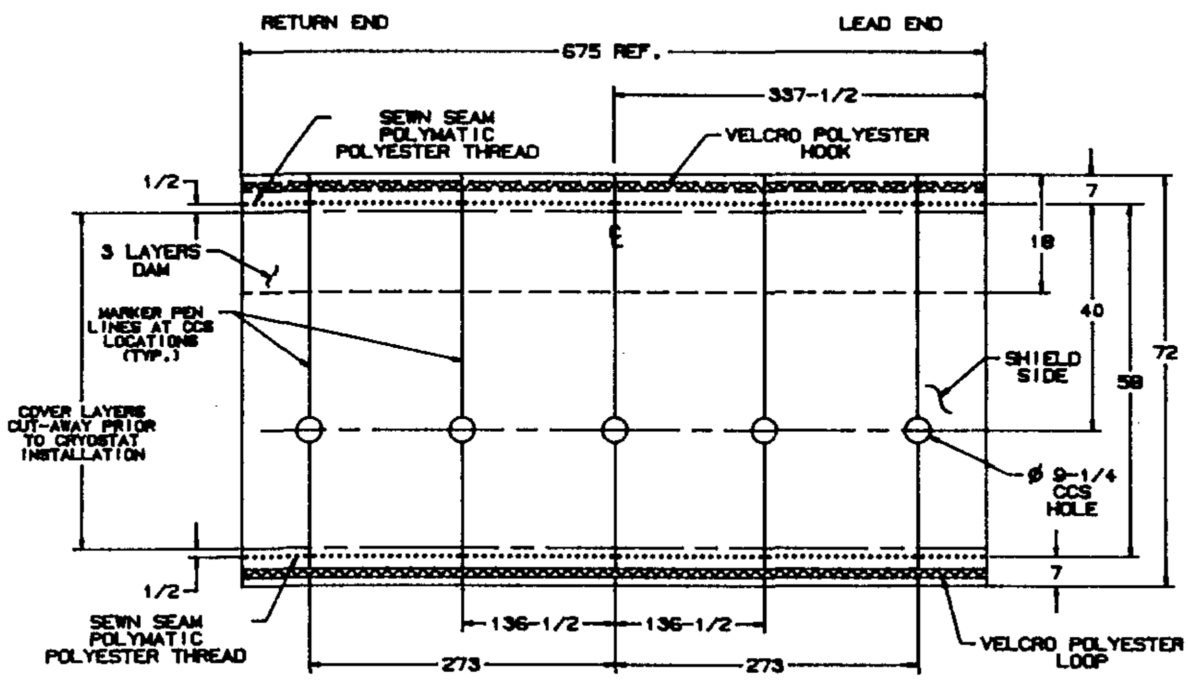
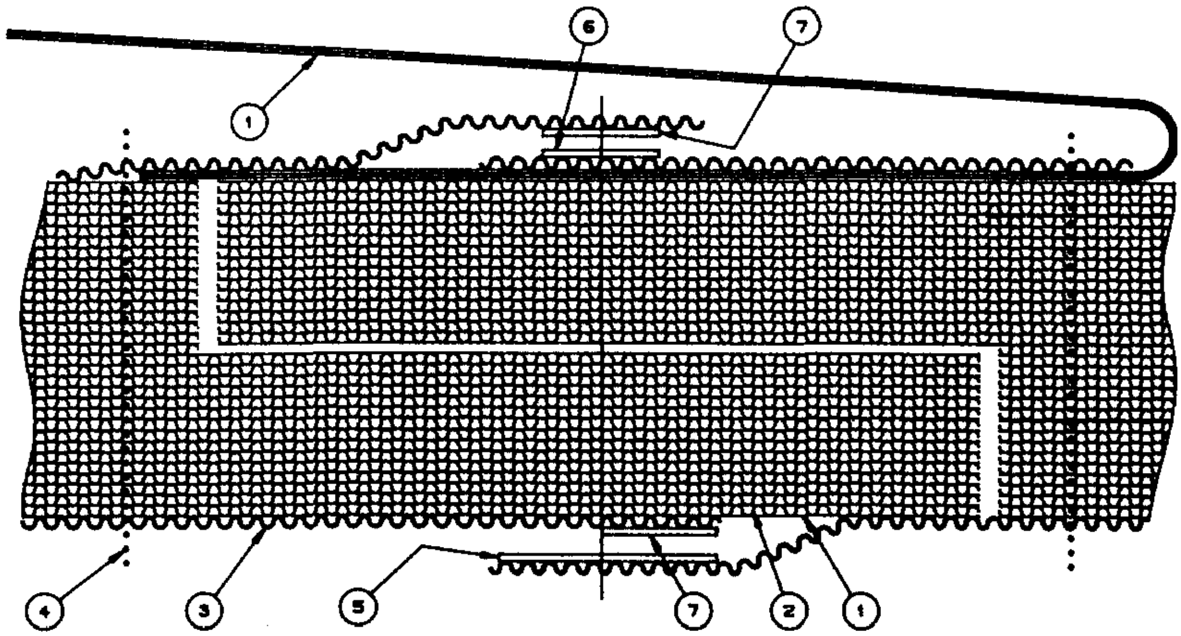


Fig. 3. SSC Dipole Magnet 80K Inner Blanket

BLANKET INSTALLATION

The tightness of the blanket wrap during installation in the SSC cryostat is fixed by the blanket design. Parallel velcro strips sewn to the outer blanket layers serve to secure the blanket at installation. The velcro strips are separated by a distance determined empirically for each blanket (20K, 80K inner and 80K outer) by trial fitting blanket sections onto actual shields and adjusting the velcro separation until the desired blanket fit around the shield was obtained. Since both edges of the blanket are sewn, the MLI material locked between seams is caused to wrinkle or wave as the blanket is wrapped around the shield. This wrinkling occurs as a result of the regimented layers being unable to separately slide across each other as would be the case, for example, if only one edge of the blanket were sewn. Because of layer-to-layer registration, these wrinkles or waves usually have a uniform thickness along the wave that is approximately the same thickness as in the main body of the blanket. The MLI layer density is therefore little affected by the wrinkles. Furthermore, a favorable element of these wrinkles is that they provide added material for thermal contraction of the blankets.

At installation, the MLI blanket is wrapped around the shield such that edges of the blanket overlap. As the edges are drawn together, tension on the blanket from pulling the blanket against the shield is taken by the sewn seams and the cover layers. The material located in the greater blanket area between the sewn seams is isolated from the tension by the seams. Next to the shield surface, opposite edges of the lower cover layer are secured to each other by the full-width engagement of the velcro strips. The overlapped edges of the MLI layers are then joined along the entire blanket length using a stepped-butted-joint geometry. See Fig. 4. The upper cover layer edges are drawn together over the stepped joint and secured by the full-width engagement of the upper velcro strips. The completed blanket installation and stepped-butted-joint are doubly secured from opening by the two velcro pairs.



BLANKET MATERIALS:
1) DOUBLE ALUMINIZED POLYESTER (DAM).
2) REEMAY SPUNBONDED POLYESTER NO. 2250 (RSP).
3) REEMAY SPUNBONDED POLYESTER NO. 2295 (RSP).
4) BELDING POLYMATIC POLYESTER (WHITE) THREAD (V125).
5) VELCRO WOVEN POLYESTER HOOK (2").
6) VELCRO WOVEN POLYESTER HOOK (1").
7) VELCRO WOVEN POLYESTER LOOP (1").

Fig. 4. MLI Stepped/Butted Seam

DISCUSSION

A unique feature of this blanket design and installation technique is that it eliminates the need for MLI tape (aluminized adhesive tape) to secure the blanket. This distinction is immediately realized as a gain to the ultimate obtainable vacuum that the SSC might expect. The elimination of MLI tape from the cryostat vacuum space would preclude: 1) adhesive outgassing from the tape; 2) virtual leaks of trapped gases from between the tape and the taped surface; and 3) increased deterioration of the MLI materials due to reaction of the evolved gases with chemical radicals formed in the MLI by irradiation during the lifetime of the SSC accelerator.

CONCLUSIONS

The apparatus and blanket fabrication method is a cost effective means to mass produce dimensional uniform MLI blankets:

1) it reduces the number of production personnel necessary to fabricate a finished blanket;
2) it eliminates layer by layer handling of the MLI materials, thereby greatly reducing labor costs and insuring interlayer cleanliness;
3) it allows precise location and insertion of penetrations or holes in the MLI to be done during blanket fabrication while the MLI is on the winding mandrel.

Incorporated with the blanket design are fasteners which automate decision making during installation of the MLI blankets into an SSC cryostat. The blanket design guarantees that each MLI installation is identically reproduced in a straight-forward manner. By virtue of the blanket design, the apparatus, and the fabrication method, the MLI installation geometry in each of the 10,000 cryostats will be dimensional uniform. By providing positive control of the dimensional parameters which contribute to the MLI blanket thermal performance, consistent and predictable operational performance of the MLI system is replicated in the 10,000 SSC cryostats.

REFERENCES

1. SSC Central Design Group, Superconducting super collider magnet system requirements, SSC-MAG-D-101 (JULY 23, 1987).
2. R.C. Niemann, et. al., Model SSC dipole magnet cryostat assembly, presented at the IISSC, February 8-10, 1989, New Orleans, LA.
3. J.W. Price, Measuring the gas pressure within a high performance insulation blanket, in: "Advances in Cryogenic Engineering," Vol. 13, Plenum Press, New York (1967).
4. A.P.M. Glassford and C.K. Liu, Outgassing rate of multilayer insulation materials at ambient temperature, J. Vac. Sci. Technol., 17:696.
5. W. Burgess and Ph. Lebrun, Compared performance of Kapton and Mylar based superinsulation, in: "Proceedings of the Tenth International Cryogenic Engineering Conference," Helsinki, Finland (1984).
6. H. Burmeister, et. al., Test of multilayer insulations for use in the superconducting proton-ring of HERA, in: "Advances in Cryogenic Engineering," Vol. 33, Plenum Press, New York (1987).
7. M.H Van de Voorde and C. Restat, Selection guide to organic materials for nuclear engineering, CERN 72-7 (1972).
8. DuPont & Co., Industrial Films Div.; and, Textile Fibers Dept.
9. James River Corporation, Nonwoven Division.